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## Search for Lepton Flavor Violating $\tau$ Decays at $B$ -factories

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### Abstract

Lepton flavor violations in charged lepton give good signatures for the new physics. We review recent searches for lepton flavor violation in  $\tau^-$  decays at  $B$ -factories. In these searches, optimization for background reduction is important to obtain high sensitivity. No evidence for these decays is observed and 90% confidence level upper limits have been set on the branching fractions at the  $O(10^{-8})$  level.

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# 1 Introduction

Lepton-flavor-violating (LFV) decays of charged leptons are expected to have negligible probability even including neutrino oscillations in the Standard Model (SM). The branching fractions of  $\tau^- \rightarrow \mu^- \gamma$  including SM+ neutrino oscillations are less than  $O(10^{-40})$  [1]. However, many extensions of SM, such as supersymmetry (SUSY) and large extra dimensions, predict enhanced LFV decays with branching fractions close to the current experimental sensitivity [2, 3, 4, 5, 6]. With certain combinations of new physics parameters, the branching fractions for LFV  $\tau$  decays can be as high as  $10^{-7}$ , which is already accessible in high-statistics  $B$ -factory experiments. Therefore, an observation of LFV decay will be a clear signature for new physics beyond the SM.  $\tau$  leptons are expected to be coupled strongly with new physics and have many possible LFV decay modes due to their large mass. Therefore,  $\tau$  leptons are ideal objects to search for the LFV decays.

SUSY, which is the most popular candidate among New Physics (NP) models, induces naturally LFV at one-loop through the scalar lepton mixing. The  $\tau^- \rightarrow \ell^- \gamma$  modes, where  $\ell^-$  is either an electron or a muon, are important and have the largest branching fraction in the SUSY seesaw model. The predicted branching fraction of  $\tau^- \rightarrow \mu^- \gamma$  is written as

$$\mathcal{B}(\tau^- \rightarrow \mu^- \gamma) = 3.0 \times 10^{-6} \times \left( \frac{\tan \beta}{60} \right)^2 \left( \frac{1 \text{ TeV}}{M_{\text{SUSY}}} \right)^4 \quad (1)$$

where  $M_{\text{SUSY}}$  is the typical SUSY mass and  $\tan \beta$  is the ratio of two Higgs vacuum expectation values [7]. If  $M_{\text{SUSY}}$  is small and  $\tan \beta$  is large, this decay mode is enhanced up to current experimental sensitivity.

If a typical SUSY mass is larger than  $\sim 1$  TeV, processes via one-loop contributions with SUSY particles are suppressed. When scalar leptons are much heavier than weak scale, LFV occurs via a Higgs-mediated LFV mechanism. If LFV occurs via a Higgs-mediated LFV mechanism,  $\tau^-$  leptons can decay into  $\ell^- f_0(980)$ , through a scalar Higgs boson. The decays  $\tau^- \rightarrow \ell^- \pi^0$ ,  $\ell^- \eta$  and  $\ell^- \eta'$  are mediated by a pseudoscalar Higgs boson while  $\tau^- \rightarrow \ell^- \mu^+ \mu^-$  can be mediated through both scalar and pseudoscalar Higgs bosons [8].

The ratios between theoretically predicted branching fractions of  $\tau^- \rightarrow \mu^- \gamma$ ,  $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ , and  $\tau^- \rightarrow \mu^- e^+ e^-$  and maximum theoretical branching fraction of the  $\tau^- \rightarrow \mu^- \gamma$  mode are summarized in Table 1. Since the ratio of the branching ratios allows to discriminate between new physics models, model-independent searches for various LFV modes are very important.

	SUSY+Seesaw	Higgs mediated	Little Higgs	non-universal $Z'$
$\frac{\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)}{\mathcal{B}(\tau^- \rightarrow \mu^- \gamma)}$	$\sim 2 \times 10^{-3}$	$0.06 \sim 0.1$	$0.04 \sim 0.4$	$\sim 20$
$\frac{\mathcal{B}(\tau^- \rightarrow \mu^- e^+ e^-)}{\mathcal{B}(\tau^- \rightarrow \mu^+ \gamma)}$	$\sim 1 \times 10^{-2}$	$\sim 1 \times 10^{-2}$	$0.04 \sim 0.4$	$\sim 2020$
$\frac{\mathcal{B}(\tau^- \rightarrow \mu^- \gamma)}{\mathcal{B}(\tau^- \rightarrow \mu^- \gamma)}$	$< 10^{-7}$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-9}$

Table 1: Ratios between the branching fractions of the  $\tau^- \rightarrow \mu^- \gamma$  and  $\tau^- \rightarrow \mu^- \ell^+ \ell^-$  modes and the maximum theoretical branching fraction of the  $\tau^- \rightarrow \mu^- \gamma$  mode in various new physics models.

## 2 KEKB/Belle and PEP-II/BaBar

The KEKB is a  $e^+e^-$  asymmetric-energy collider operating at the center-of-mass (CM) energy corresponding to the  $\Upsilon(4S)$  resonance. KEKB have achieved the world highest peak luminosity of  $2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . Experiments at the energy of  $\Upsilon(4S)$  allow searches for LFV decays with a very high sensitivity since the cross section of  $\tau^+\tau^-$  production is  $\sigma_{\tau\tau} \simeq 0.9 \text{ nb}$ , close to that of  $B\bar{B}$  production,  $\sigma_{B\bar{B}} \simeq 1 \text{ nb}$ , and thus,  $B$ -factories are also excellent  $\tau$ -factories. The Belle detector [9] operating at the KEKB  $B$ -factory [10] accumulated about  $9 \times 10^8$   $\tau$  pairs. Similarly, the BaBar detector, described in more detail elsewhere [11], collected data at the PEP-II asymmetric-energy  $e^+e^-$  collider that operated at a CM energy of 10.58 GeV. Finally, a  $557 \text{ fb}^{-1}$  data sample has been accumulated before the PEP-II collider stopped running. Both detectors at  $B$ -factories are the multipurpose detectors with good track reconstruction and particle identification ability.

## 3 Analysis Method

All searches for LFV  $\tau$  decays follow a similar pattern. We search for  $\tau^+\tau^-$  events in which one  $\tau$  (signal side) decays into an LFV mode under study, while the other  $\tau$  (tag side) decays into one (or three) charged particles and any number of additional photons and neutrinos (for example, see Fig. 1). To search for exclusive decay modes, we select low-multiplicity events with zero net charge, and separate a signal- and tag-side into two hemispheres using a thrust axis. The backgrounds in such searches are dominated by continuum  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ), generic  $\tau^+\tau^-$ , two-photon,  $\mu^+\mu^-$  and Bhabha events. To obtain good sensitivity, we optimize the event selection using particle identification and kinematic information for each mode separately.

After signal selection criteria are applied, signal candidates are examined in the two-dimensional space of the invariant mass,  $m_{\text{inv}}$ , and the difference of their energy

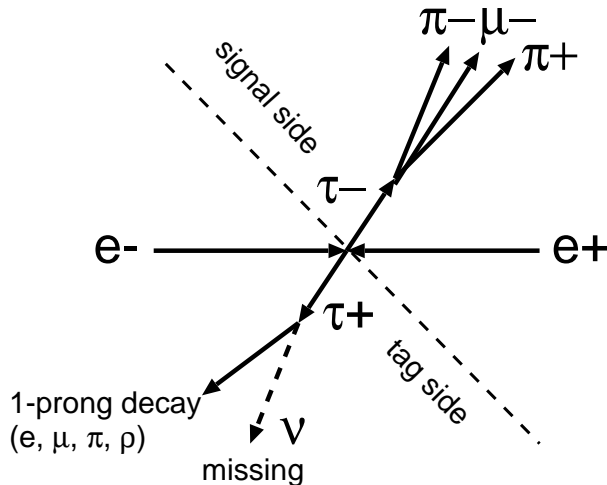


Figure 1: Event signature of LFV  $\tau^-$  decay in a case of  $\tau^- \rightarrow \mu^- \pi^+ \pi^-$  analysis

from the beam energy in the center-of-mass (CM) system,  $\Delta E$ . A signal event should have  $m_{\text{inv}}$  close to the  $\tau$ -lepton mass and  $\Delta E$  close to 0 GeV. We blind a region around the signal region in the  $m_{\text{inv}} - \Delta E$  plane so as not to bias our choice of selection criteria. The expected number of background events in the blind region and systematic uncertainties are first evaluated, and then the blind region is opened and candidate events are counted. By comparing the expected and observed numbers of events, we either observe a LFV  $\tau$  decay or set an upper limit by applying Bayesian, Friedman-Cousins or maximum likelihood approaches.

## 4 Results

### 4.1 $\tau^- \rightarrow \ell^- \gamma$

Belle have obtained upper limits for the branching fraction at the 90% confidence level  $\mathcal{B}(\tau^- \rightarrow \mu^- \gamma) < 4.5 \times 10^{-8}$  and  $\mathcal{B}(\tau^- \rightarrow e^- \gamma) < 1.2 \times 10^{-7}$  [12] using  $535 \text{ fb}^{-1}$  of data. The dominant background for these modes comes from generic  $\tau\tau$  events where one  $\tau$  decays into  $\ell \nu \bar{\nu}$  with initial state radiation. Since many background events from  $\tau\tau$  with initial state radiation remain, our sensitivity is limited.

BaBar updated the search for  $\tau^- \rightarrow \ell^- \gamma$  using their final data set of  $470 \text{ fb}^{-1}$  on  $\Upsilon(4S)$ ,  $31 \text{ fb}^{-1}$  on  $\Upsilon(3S)$  and  $15 \text{ fb}^{-1}$  on  $\Upsilon(2S)$ , which corresponds to  $(963 \pm 7) \times 10^6$   $\tau$  decays. In this analysis, new kinematic cuts and a neural-net discriminator were applied. The  $m_{\text{inv}} - \Delta E$  distributions are shown in Fig. 2. The efficiency was 6.1 and 3.9% for the  $\tau^- \rightarrow \mu^- \gamma$  and  $e^- \gamma$  modes, respectively. The number of expected

background events was  $3.6 \pm 0.7$  and  $1.6 \pm 0.4$  while observed number of data in the signal region are 2 and 0 events for the  $\tau^- \rightarrow \mu^- \gamma$  and  $e^- \gamma$  modes, respectively. BaBar set the upper limits of branching fraction to be  $< 4.4 \times 10^{-8}$  and  $< 3.3 \times 10^{-8}$  for the  $\tau^- \rightarrow \mu^- \gamma$  and  $\tau^- \rightarrow e^- \gamma$  modes at the 90% CL, respectively [13].

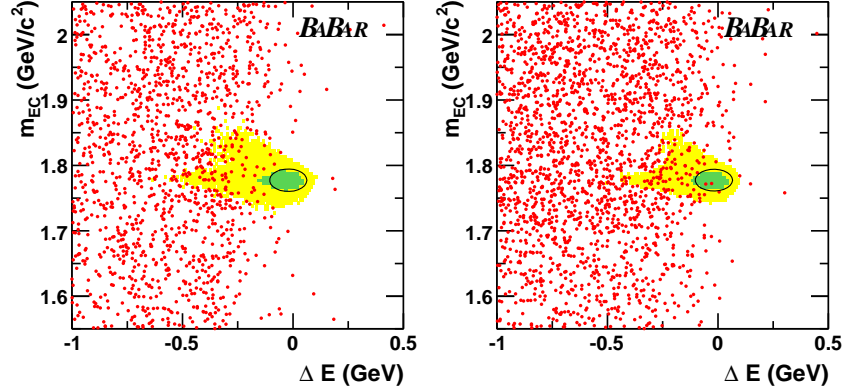


Figure 2:  $m_{\text{inv}}\text{-}\Delta E$  distributions for  $\tau^- \rightarrow e^- \gamma$  and  $\tau^- \rightarrow \mu^- \gamma$  from the BaBar analysis. Data are shown as dots and contours containing 90% (50%) of signal MC events are shown as yellow- (green-) shaded regions. The elliptical signal regions shown by a solid curve are used for evaluating the signal yield.

## 4.2 $\tau^- \rightarrow \ell^- \eta, \ell^- \eta', \ell^- \pi^0$

Belle and BaBar have published the results of the search for the  $\tau^-$  decays into a lepton and a neutral pseudoscalar ( $\pi^0, \eta, \eta'$ ) using around  $400\text{fb}^{-1}$  of data, and have set the range of the upper limits of  $(0.8 - 2.4) \times 10^{-7}$  at 90% CL. [14, 15]

Belle updated a search for these modes using  $901\text{fb}^{-1}$  of data. By introducing new event selections with a neural-net discriminator and studying the background components in detail, they obtain larger efficiencies than previous analysis in a factor of around 1.5 in the averages, and the expected numbers of the background events in the signal region are achieved to suppress less than one events for each mode. One event is found in the signal region for the  $\tau^- \rightarrow e^- \eta (\rightarrow \gamma \gamma)$  mode while no event is observed in other modes (see Fig. 3). Therefore, no evidence for these decays is observed and Belle sets preliminary 90% confidence level upper limits on the branching fractions between  $(2.2 - 4.4) \times 10^{-8}$ .

## 4.3 $\tau^- \rightarrow \ell V^0$

Previously, Belle obtained 90% confidence level (C.L.) upper limits on branching fractions of these decays using  $543\text{fb}^{-1}$  of data, and these results were in the range

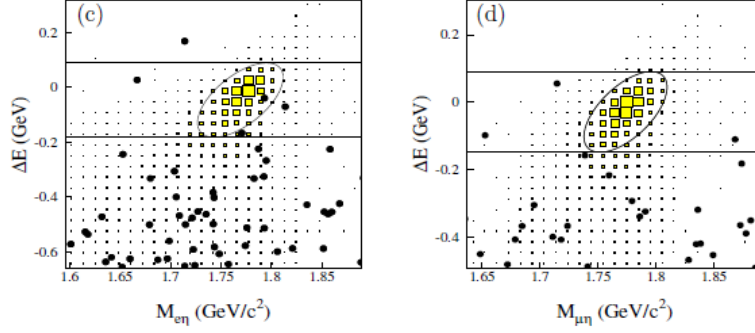


Figure 3:  $m_{\text{inv}}\text{-}\Delta E$  distributions for the  $\tau^- \rightarrow e^- \eta (\rightarrow \gamma\gamma)$  (left) and  $\tau^- \rightarrow \mu^- \eta (\rightarrow \gamma\gamma)$  (right) from the Belle analysis. Data and signal MC events are shown as dots and histogram. The elliptical signal regions shown by a solid curve are used for evaluating the signal yield.

$(5.8\text{--}18) \times 10^{-8}$  [16]. The BaBar collaboration has also published 90% C.L. upper limits in the range  $(2.6\text{--}19) \times 10^{-8}$  using  $451 \text{ fb}^{-1}$  of data [17] for all  $\tau^- \rightarrow \ell^- V^0$  decays except for  $\tau^- \rightarrow \ell^- \omega$  for which  $384 \text{ fb}^{-1}$  of data were used [18].

Belle updates an search for these modes based on a data sample of  $854 \text{ fb}^{-1}$  of data. To improvement better results than previous analysis, we use a larger data sample and apply improved rejections of specific backgrounds, such as di-baryon production in the continuum for the  $\tau^- \rightarrow \mu^- V^0$  modes, and  $\tau^- \rightarrow h^- \pi^0 \nu_\tau$  decays with a photon conversion for the  $\tau^- \rightarrow e^- V^0$  modes. Since no evidence for a signal after event selections is found, we set the following 90% C.L. upper limits on the branching fractions:  $\mathcal{B}(\tau^- \rightarrow e^- V^0) < (1.8 - 4.8) \times 10^{-8}$  and  $\mathcal{B}(\tau^- \rightarrow \mu^- V^0) < (1.2 - 8.4) \times 10^{-8}$  [19] (for example, see Fig. 4). These results improve upon our previously published upper limits by factors of up to 5.7.

#### 4.4 $\tau \rightarrow \ell h h'$

Belle and BaBar have also searched for various  $\ell h h'$  (where  $h, h' = \pi^\pm$  or  $K^\pm$ ) modes including lepton flavor and lepton number violation ( $\tau^- \rightarrow \ell^- h^- h'^+$  and  $\tau^- \rightarrow \ell^+ h^- h'^-$ ) with the range of upper limits:  $(7\text{--}48) \times 10^{-8}$  [20] and  $(5.8\text{--}18) \times 10^{-8}$  [21] using  $221 \text{ fb}^{-1}$  and  $543 \text{ fb}^{-1}$  of data, respectively.

Belle recently updated a search for these modes using  $854 \text{ fb}^{-1}$  of data. Basically, Belle applies similar event selections to  $\tau^- \rightarrow \ell^- V^0$  analysis due to same signature as  $\tau \rightarrow \ell V^0 (\rightarrow h h')$  in the final state. However, the remaining background events for these modes are larger than  $\tau^- \rightarrow \ell^- V^0$  modes since there is no requirements to reconstruct  $V^0$  mesons. Therefore, Belle applies additional tighter selection as missing informations, for example. After event selection, Belle observes one events

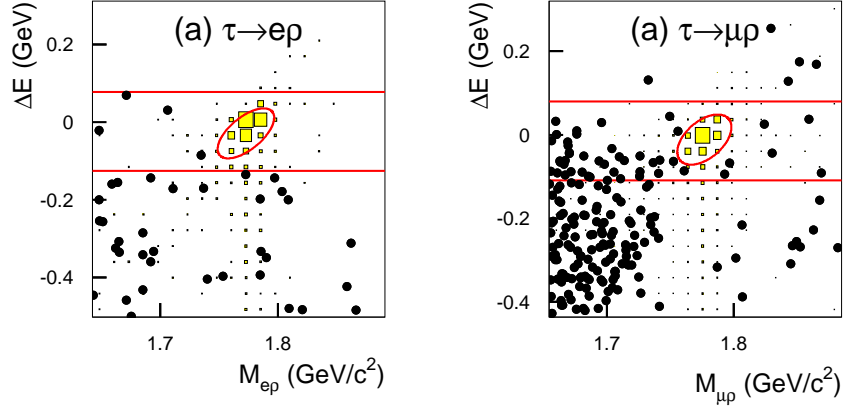


Figure 4:  $m_{\text{inv}}\text{-}\Delta E$  distributions for the  $\tau^- \rightarrow e^- \rho$  (left) and  $\tau^- \rightarrow \mu^- \rho$  (right) modes from the Belle analysis. Data and signal MC events are shown as dots and histogram. The elliptical signal regions shown by a solid curve are used for evaluating the signal yield.

in the signal region for the  $\tau^- \rightarrow \mu^+ \pi^- \pi^-$  and  $\tau^- \rightarrow e^+ \pi^- K^-$  modes while no events are found for the other modes. In each case, the number of events observed in the signal region is consistent with the expected number of background events. Therefore, no evidence for these decays is observed, and we set preliminary upper limits on the branching fractions at 90% C.L.:  $\mathcal{B}(\tau \rightarrow ehh') < (2.0 - 3.7) \times 10^{-8}$  and  $\mathcal{B}(\tau \rightarrow \mu hh') < (2.1 - 8.6) \times 10^{-8}$ . These results improve upon previously Belle published upper limits by factors of around 1.8 on the average.

## 5 Future Prospect

LFV sensitivity depends on the remaining background level. For the  $\tau^- \rightarrow \mu^- \gamma$  mode, there is large remaining background from generic  $\tau^+ \tau^-$  events with initial state radiation. In this case, the expected branching fraction of  $\tau^- \rightarrow \mu^- \gamma$  is scaled as  $1/\sqrt{\mathcal{L}}$ . On the other hand, the remaining background events for the  $\tau^- \rightarrow \ell^- \ell'^+ \ell''^-$  and  $\ell^- + \text{meson}$  modes are expected to be negligible at  $10 \text{ ab}^{-1}$ . Therefore, the expected branching fractions of these modes are linearly proportional to luminosity from current upper limits. Figure 5 shows the history of the obtained UL of the branching fractions as a function of the integrated luminosity, as well as the expected sensitivity extrapolating from the results. The upgraded  $B$ -factories, Belle-II and Super $B$  experiments, are planned to collect more than 10-times larger luminosity than the current one. Therefore, the expected branching fraction of  $\tau^- \rightarrow \mu^- \gamma$  at the Super  $B$ -factory is  $O(10^{-(8 \sim 9)})$  while the expected branching fractions of  $\tau^- \rightarrow \ell^- \ell'^+ \ell''^-$

and  $\ell^- + \text{meson}$  are  $O(10^{-(9\sim 10)})$ .

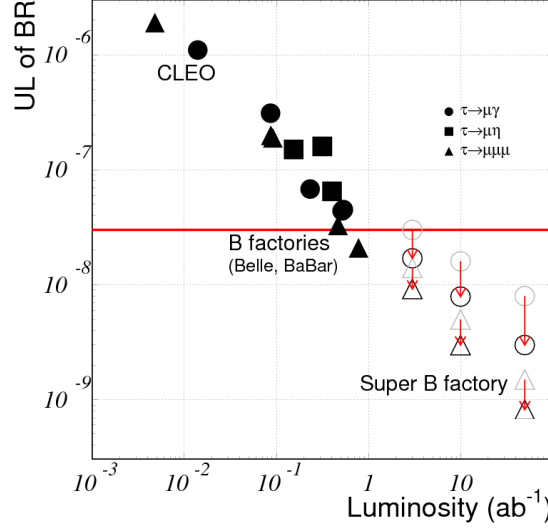


Figure 5: Branching fraction of LFV decay as a function of the integrated luminosity as well as the expected sensitivity extrapolating from the current results.

## 6 Summary

We have searched for all major modes of lepton-flavor-violating  $\tau$  decays using  $> 10^9$   $\tau$  pairs of data collected at the  $B$ -factories as the Belle detector at the KEKB collider and the BaBar detector at the PEP-II collider. No evidence for these decays is observed and we set 90% confidence level upper limits on the branching fractions at the  $O(10^{-8})$  level, shown in Fig. 6 and Table 2. These more stringent upper limits can be used to constrain the space of parameters in various models beyond the SM.

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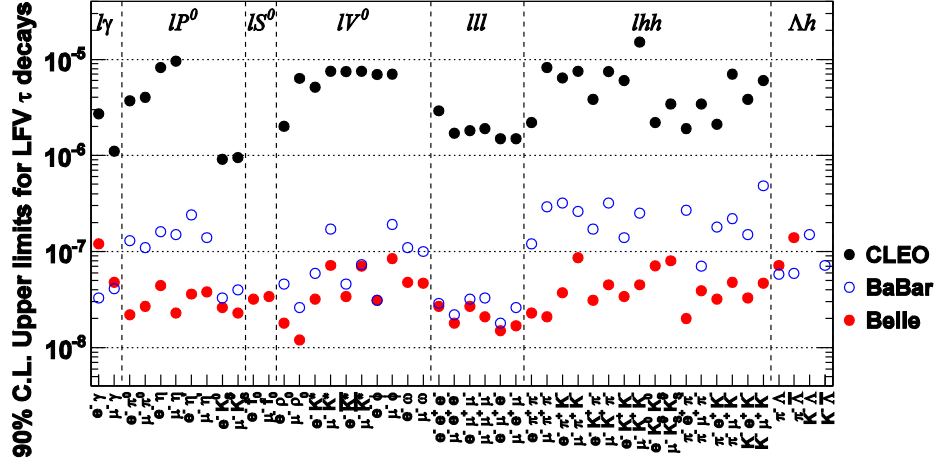


Figure 6: Upper limits of branching fraction of lepton-flavor-violating  $\tau$  decay from Belle, BaBar and CLEO.

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$\tau^-$ decay mode	Belle		BaBar	
	$\mathcal{B}, 10^{-8}$	# of $\tau^+\tau^-$	$\mathcal{B}, 10^{-8}$	# of $\tau^+\tau^-$
$\mu^-\gamma$	4.5 [12]	492M	4.4 [13]	482M
$e^-\gamma$	12 [12]	492M	3.3[13]	482M
$\mu^-\eta, \mu^-\eta', \mu^-\pi^0$	6.5-13	369M	11-20 [15]	312M
$e^-\eta, e^-\eta', e^-\pi^0$	8.0-16	369M	14-26 [15]	312M
$\ell^-\ell'^-\ell''^+$	1.5-2.7 [22]	719M	1.8-3.3 [23]	430M
$\mu^-hh'$	2.1-8.6	782M	7-44 [20]	203M
$e^-hh'$	2.0-3.7	782M	12-32 [20]	203M
$\ell^-f_0(980)(\rightarrow \pi^+\pi^-)$	3.2-3.4 [24]	617M	—	—
$\mu^-V^0$	1.2-8.4 [19]	782M	8-18 [17, 18]	414M
$e^-V^0$	1.8-4.8 [19]	782M	3.1-5.6 [17, 18]	414M
$\mu^-K_S^0$	2.3 [25]	617M	4.0 [26]	431M
$e^-K_S^0$	2.6 [25]	617M	3.3 [26]	431M
$\mu^-K_S^0K_S^0$	8.0 [25]	617M	—	—
$e^-K_S^0K_S^0$	7.1 [25]	617M	—	—

Table 2: Summary for upper limits of branching fraction of lepton-flavor-violating  $\tau$  decay

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